Neutron Optics and Instrumentation

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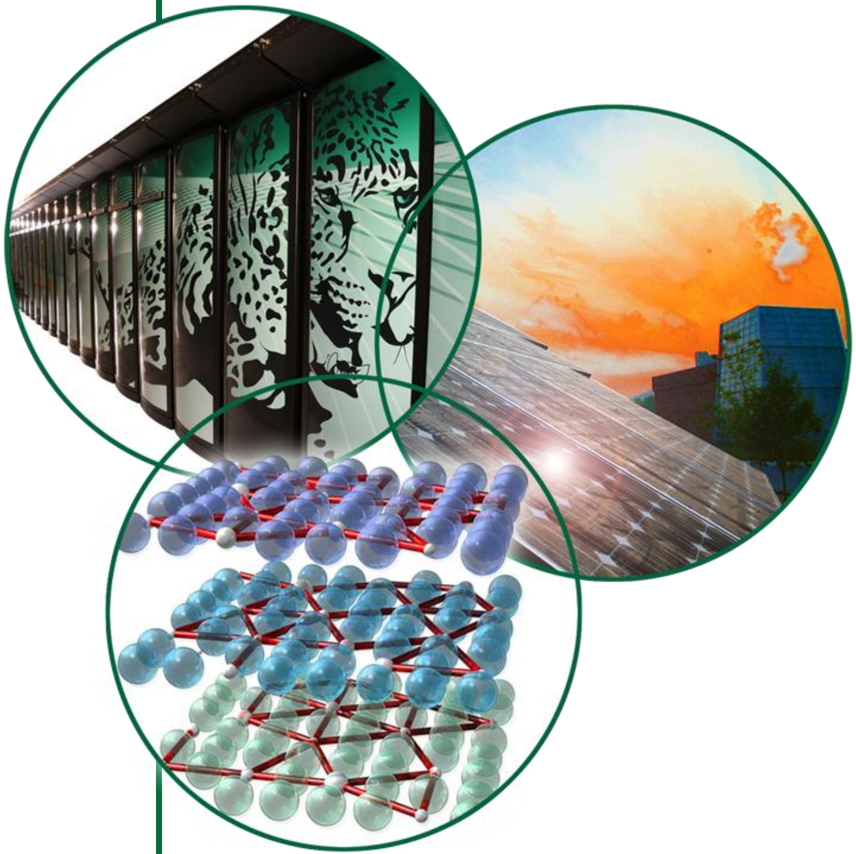
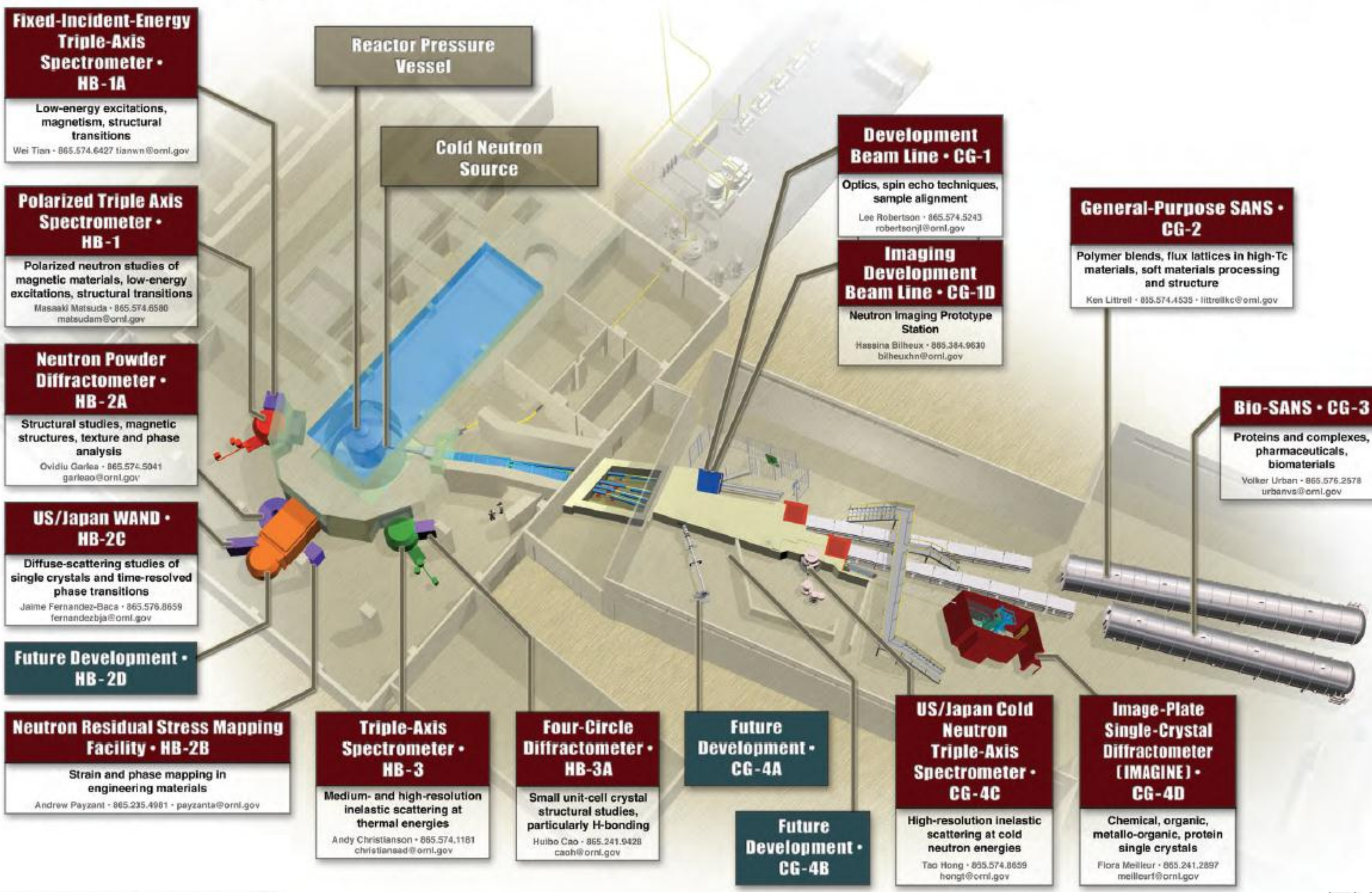


Introduction

- Neutron Sources (continuous, pulsed)
- Types of Neutron Scattering Instruments (diffraction, TOF)
- Neutron Optics (guides, supermirrors, choppers, focusing)
- Neutron Polarization (^{3}He, Heussler crystals, supermirrors)
- Neutron Detectors (LPSD, 2D-LPSD, scintillator, camera)
- Methods for Enhancing Flux (focusing optics, multi-analyzers)
- Resolution (imaging, choppers, monochromators, spin-echo, backscattering, reflectometers)
- New Instruments (new ideas under development)

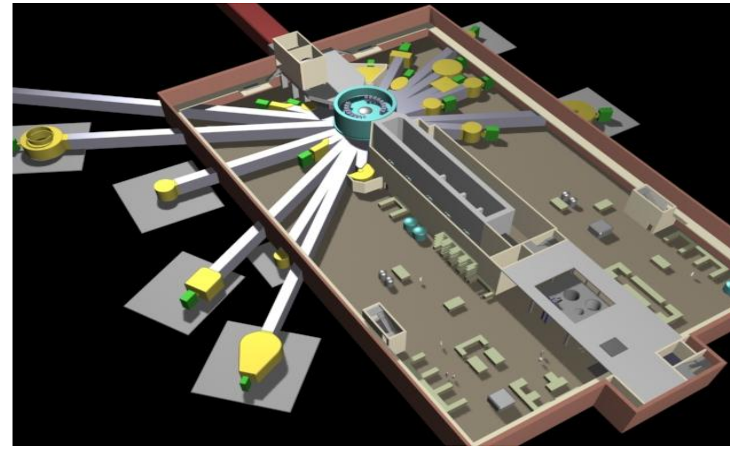
Neutron Sources: Continuous (Reactors)

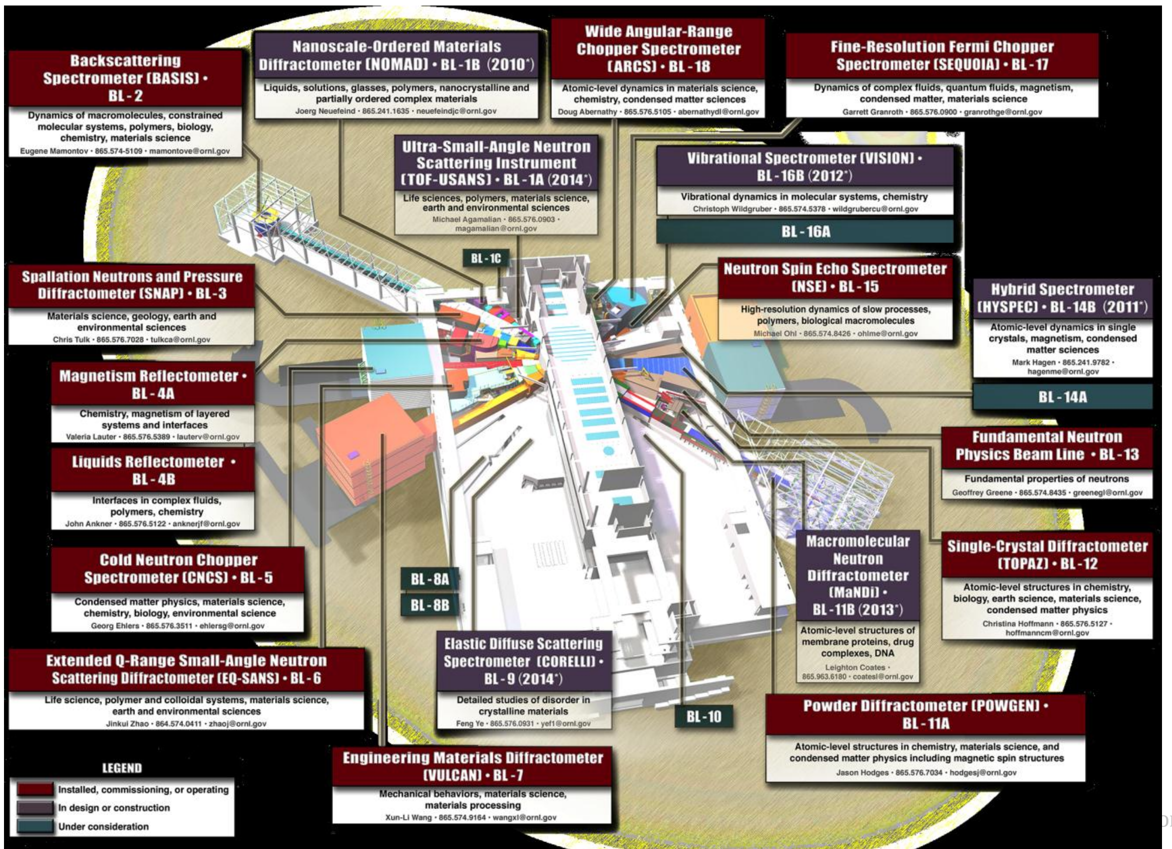
- Neutrons produces by fission (usually ^{238}U)
- Fission spectrum moderated (typically with a flux trap)

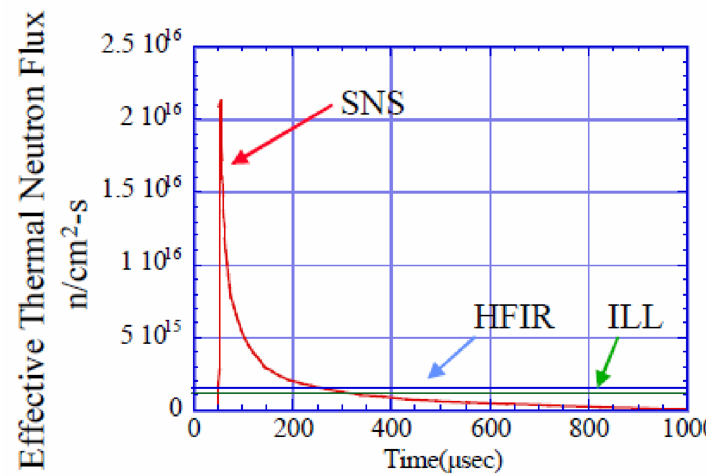


Neutron Sources: Pulsed

- Spallation Sources
  - Neutrons produced by nuclear spallation
  - Neutron beams inherently pulsed
  - Neutron energies must be moderated
  - Very high peak fluxes (10^{16} n/cm^2/s)







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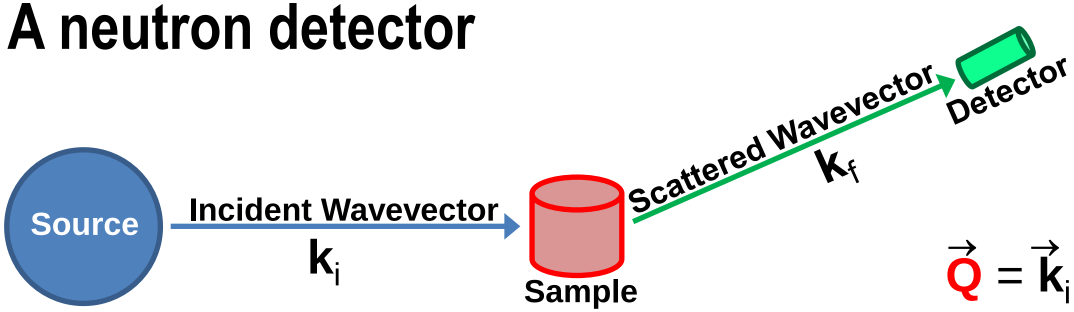
What is a Neutron Scattering Instrument?

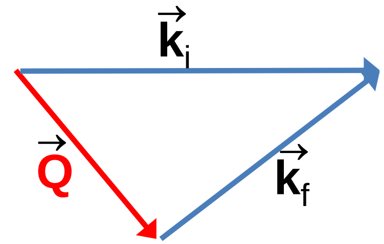
- Neutron scattering experiments measure the number of neutrons scattered by a sample as a function of the wavevector change (Q) and the energy change (E) of the neutron.

- What do we need to accomplish this?

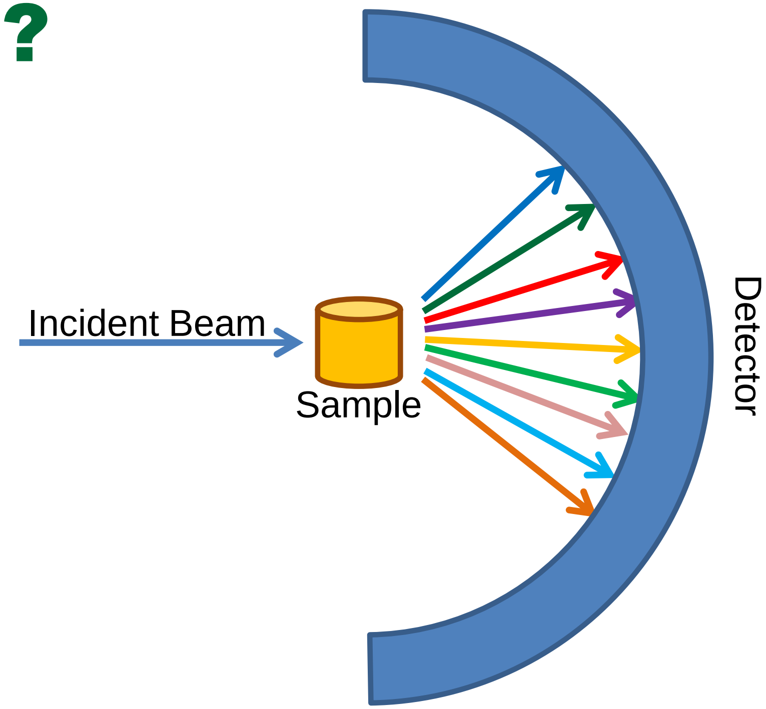
1) A source of neutrons
2) A method for selecting k_i, the wavevector of the incident neutrons
3) A very interesting sample
4) A method for determining k_f, the wavevector of the scattered neutrons
5) A neutron detector



$$\vec{Q} = \vec{k}_i - \vec{k}_f$$



Why Not Just Build a Universal Neutron Scattering Instrument That Can Do Everything We Need?



Elastic Scattering – detect all of the scattered neutrons

Inelastic Scattering – detect neutrons as a function of energy

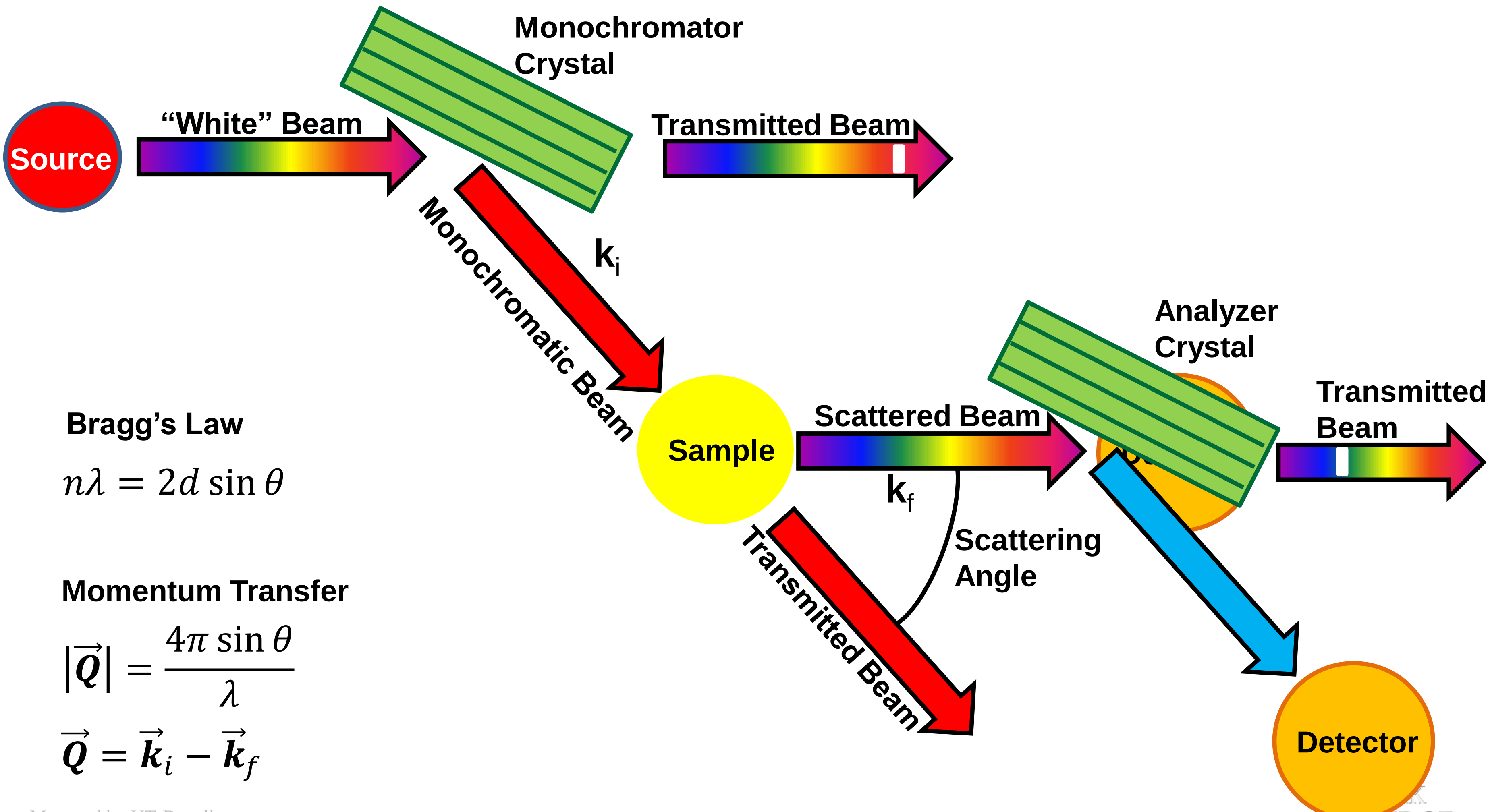
The energy of the neutron is coupled to its wavelength and velocity:

$$\lambda^2 \sim 81.81/E \text{ and } v^2 \sim 191313 \times E$$

S(Q,E) = scattering properties of the sample depend only on Q and E, not on the neutron wavelength(λ)

Message: Many different types of neutron scattering instruments are needed because the accessible Q and E ranges depend on the neutron energy and because the resolution and detector coverage have to be tailored to the science for such a signal-limited technique.

Neutron Scattering Instruments at Continuous Sources Are Typically Based on Diffraction Techniques



Bragg's Law

$$n\lambda = 2d \sin\theta$$

Momentum Transfer

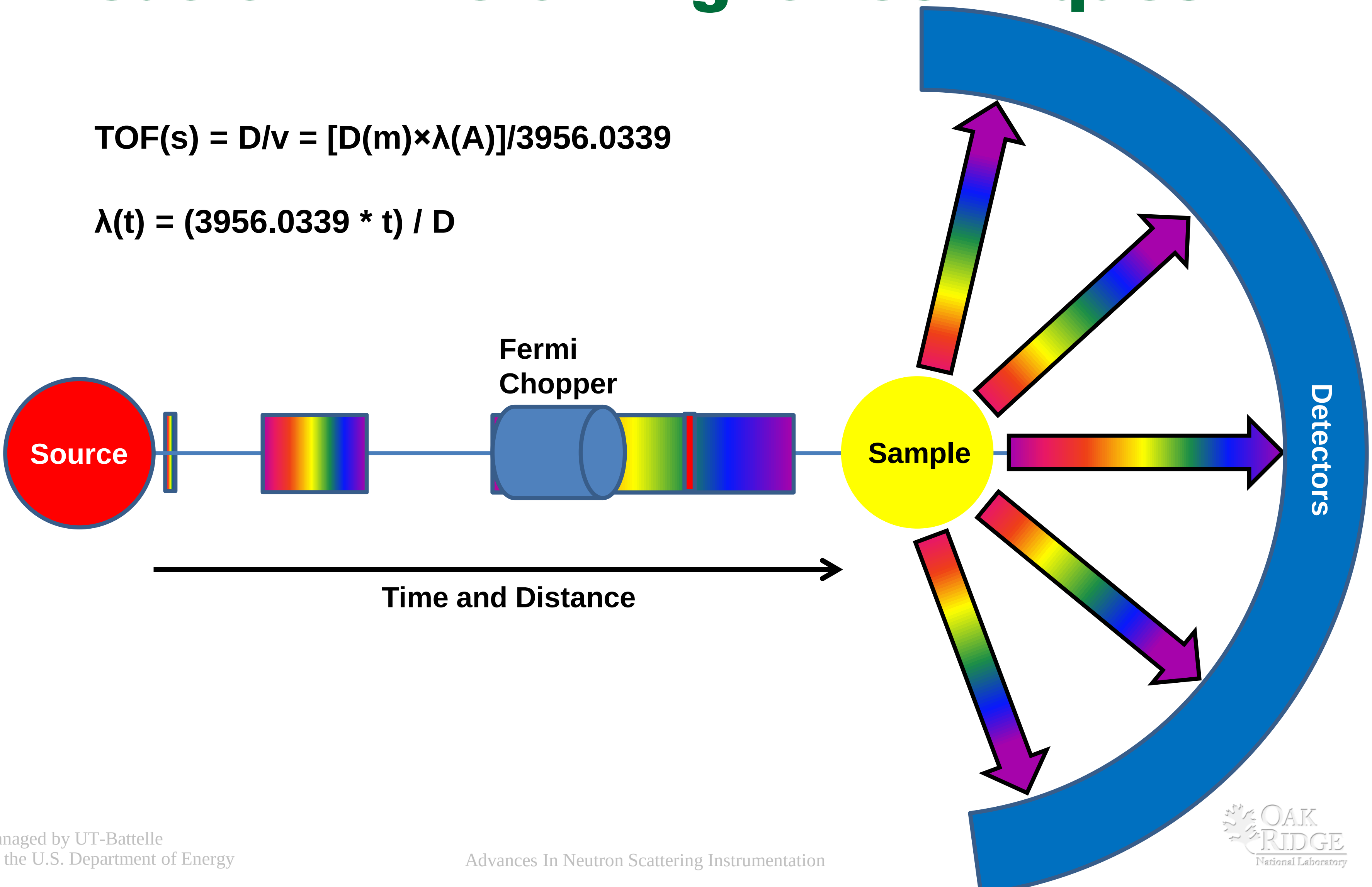
$$|\vec{\boldsymbol{Q}}| = \frac{4\pi \sin\theta}{\lambda}$$

$$\vec{\boldsymbol{Q}} = \vec{\boldsymbol{k}}_i - \vec{\boldsymbol{k}}_f$$

Neutron Scattering Instruments at Pulsed Sources Are Typically Based on Neutron Time-of-Flight Techniques

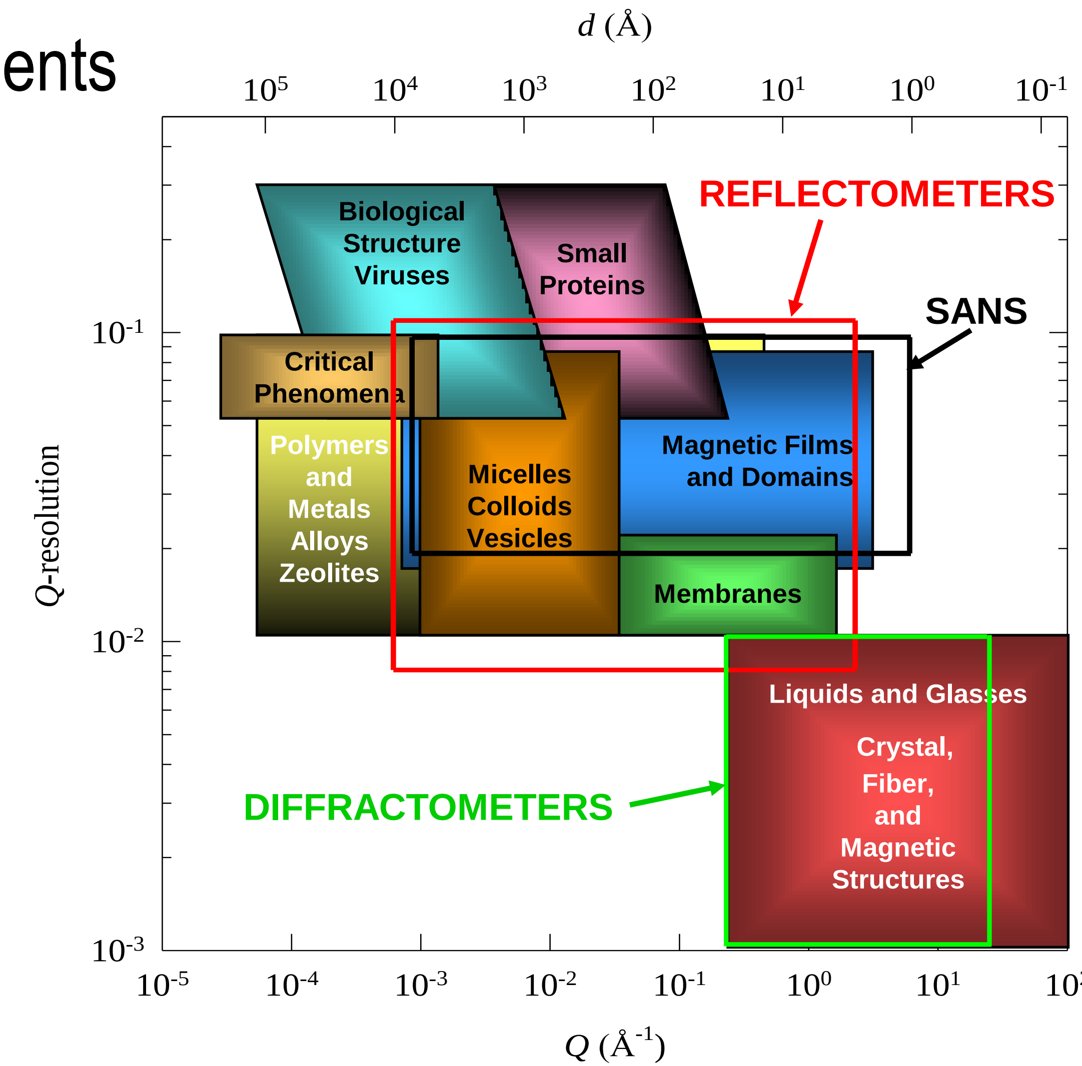
$$\mathrm{TOF(s)} = D/v = [D(m) \times \lambda(A)]/3956.0339$$

$$\lambda(t) = (3956.0339 * t) / D$$



Types of Neutron Scattering Instruments

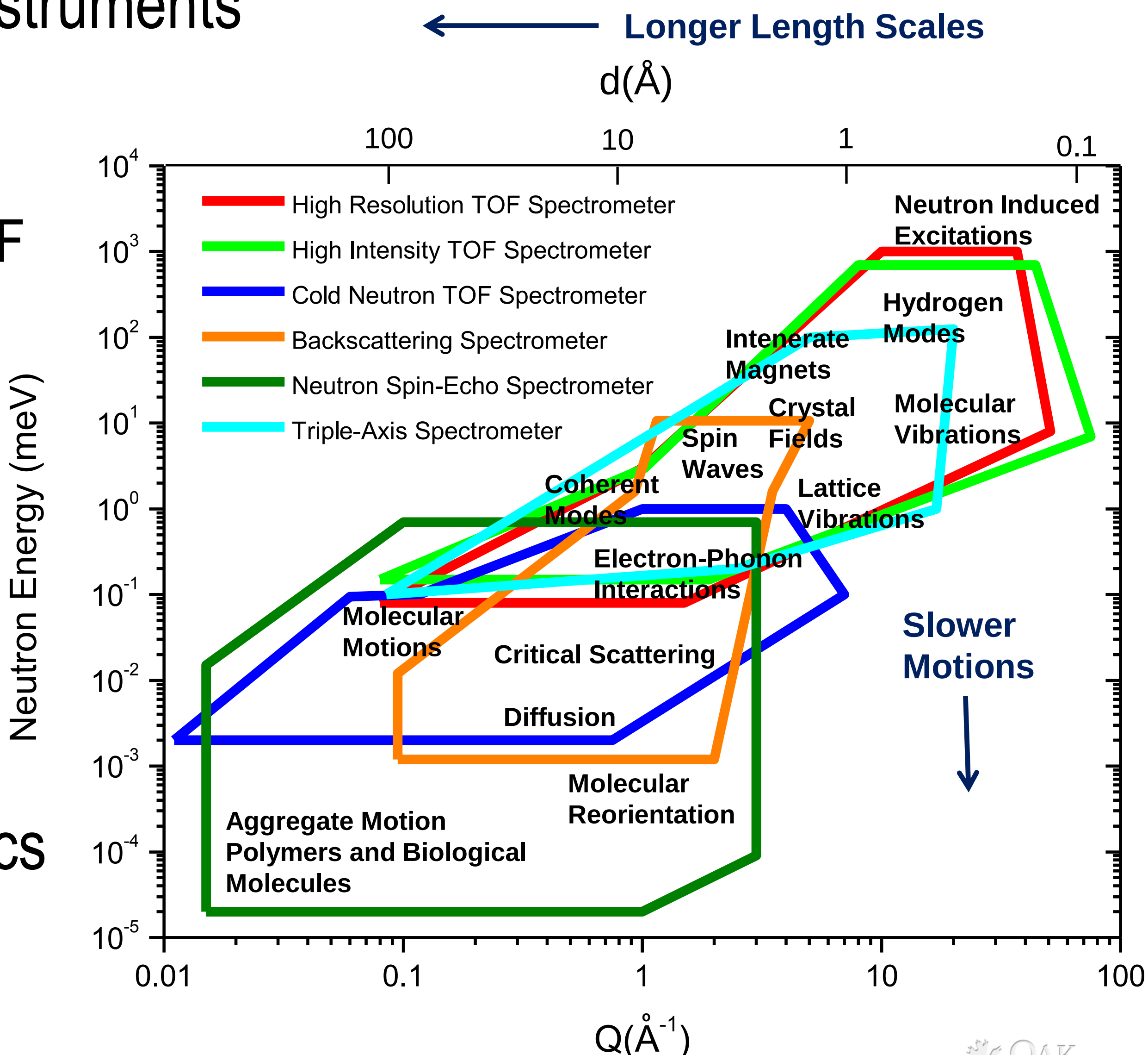
- Elastic Scattering Instruments
  - Powder diffraction
  - Single Crystal diffraction
  - SANS (typical)
  - Reflectometry
- Used to determine the average structure of materials (How the atoms are arranged).



Based on diagram by Roger Pynn

Types of Neutron Scattering Instruments

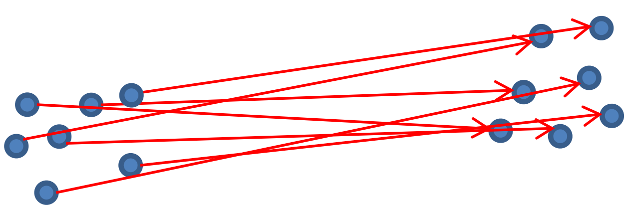
- Inelastic Scattering Instruments
  - Direct Geometry TOF Spectrometers
  - Indirect Geometry TOF Spectrometers
  - Triple-Axis Spectrometers
  - Backscattering Spectrometers
  - Neutron Spin-Echo Spectrometers
- Used to study dynamics (phonons, magnons, diffusion, …)

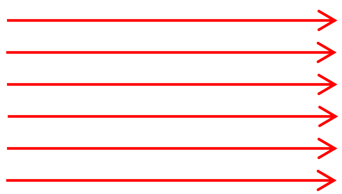


Based on diagram by Rex Hjelm

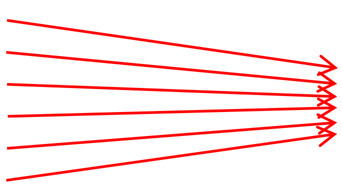
Liouville's Theorem

- In the geometrical-optics the propagation of neutrons can be represented as trajectories in a six-dimensional **phase space** (p, q), where the components of q are the generalized coordinates and the components of p are the conjugate momenta.
- Simply stated, Liouville's Theorem says that phase space volume is conserved.
- Translation: It costs flux to increase resolution and it costs resolution to increase flux.
- We can’t win and we are screwed!





Parallel



Converging

Resolution

- Uncertainty in the neutron wavelength and direction limit the precision that **Q** and E can be determined.
- When the resolution volumes in the figure are convolved, the overall resolution is approximately Gaussian (central limit theorem) and has an elliptical shape in (Q,E) space.
- The total signal observed in a scattering experiment is proportional to the phase space volume within the elliptical resolution volume – the better the resolution, the lower the count rate

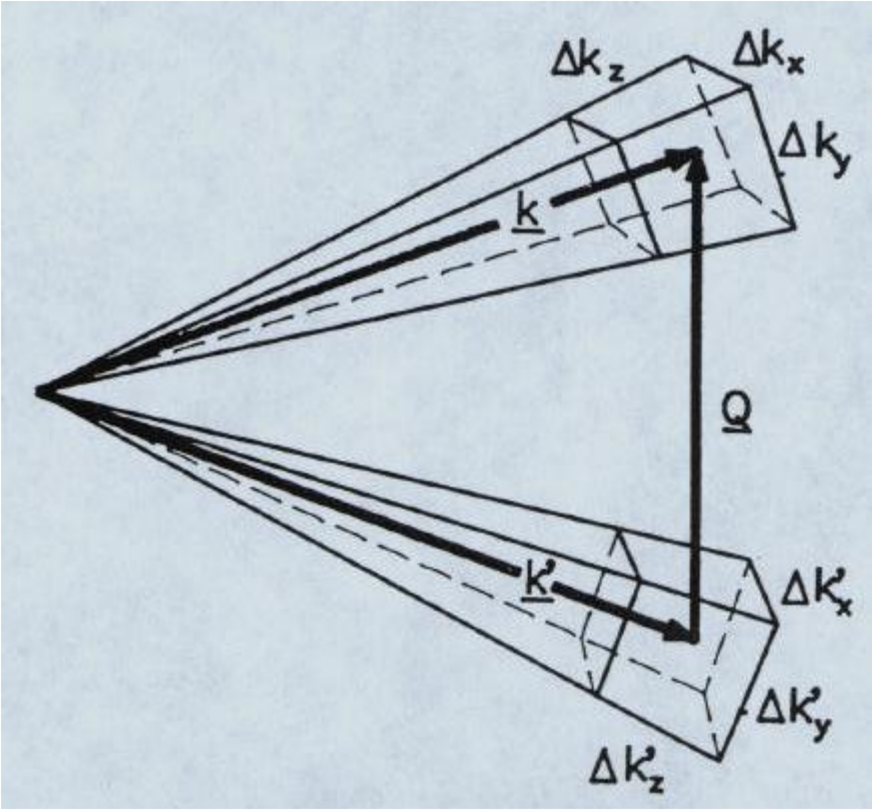


Figure borrowed from Roger Pynn

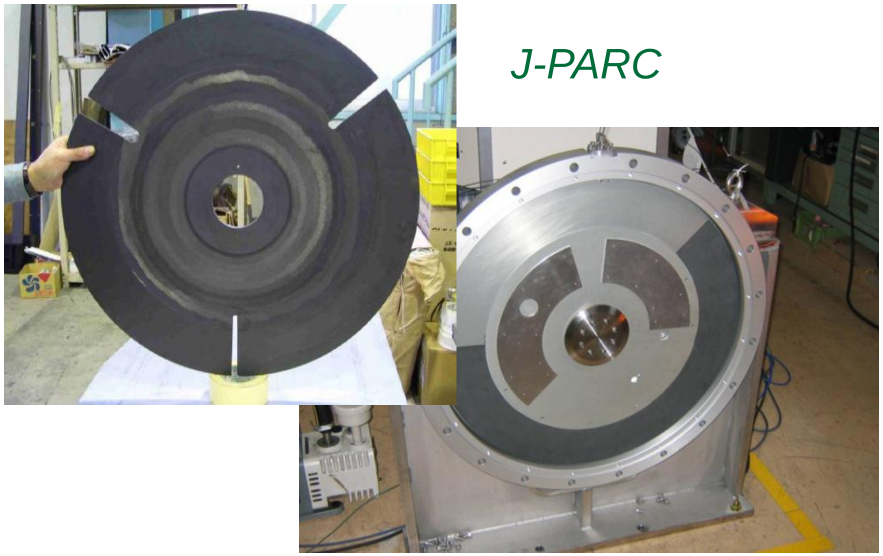
Neutron Optics

The following neutron optical components are typically used to construct a neutron scattering instrument

- **Monochromators / Analyzers:** Monochromate or analyze the energy of a neutron beam using Bragg's law
- **Choppers:** Define a short pulse of neutrons or select a small band of neutron energies
- **Guides / Mirrors:** Allow neutrons to travel large distances without suffering intensity loss
- **Polarizers / Spin Manipulators**: Manipulate the neutron spin using Lamor precession
- **Collimators:** Define the direction of travel of the neutrons
- **Detectors:** Neutron position (and arrival time for TOF) is recorded. Neutrons are typically detected via secondary ionization effects.

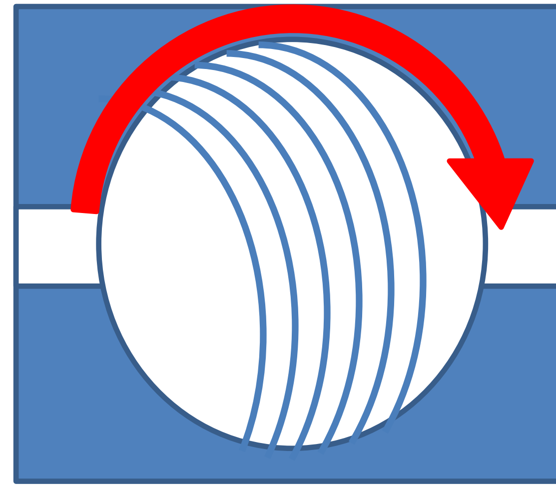
Choppers and Velocity Selectors

Disk Chopper

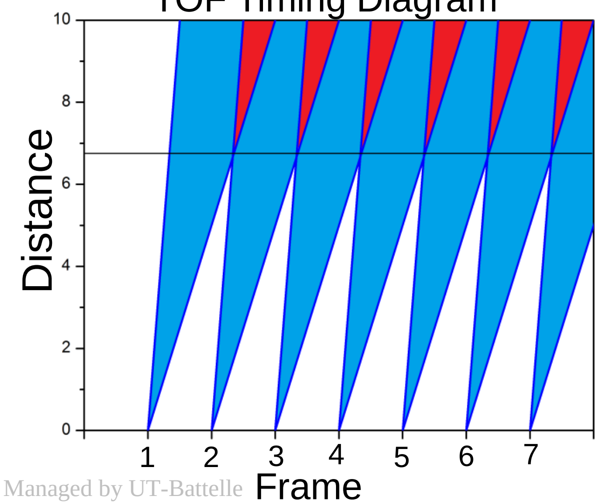


J-PARC

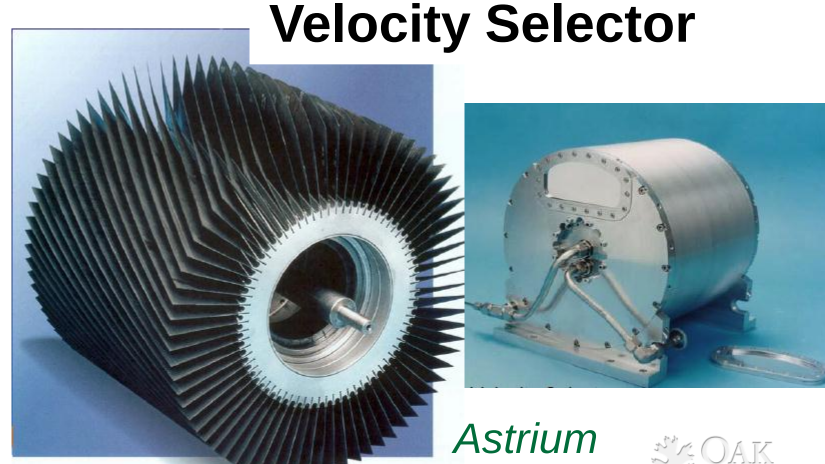
Fermi Chopper



TOF Timing Diagram

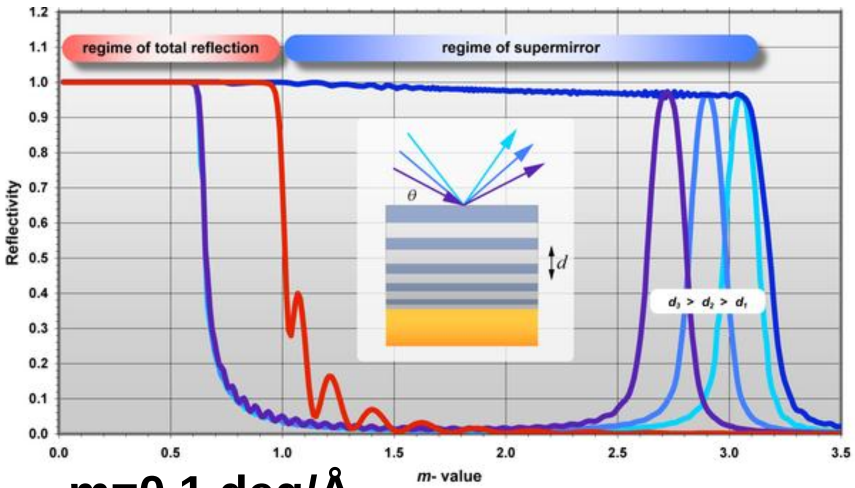


Velocity Selector

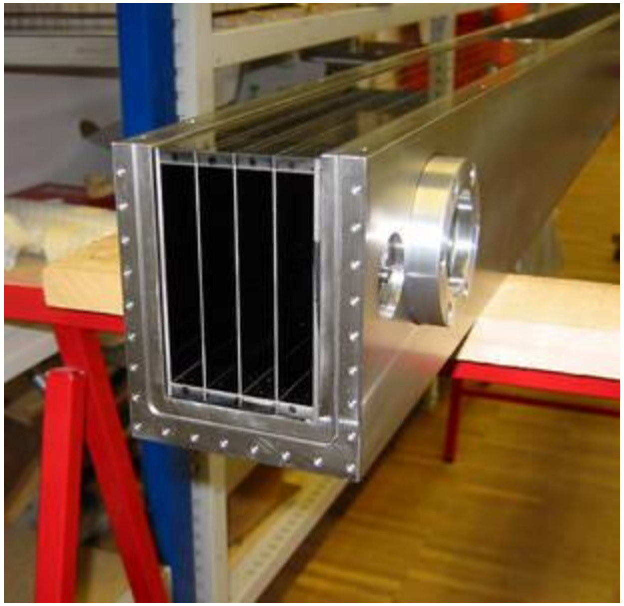


Astrium

Neutron Guides



m=0.1 deg/Å

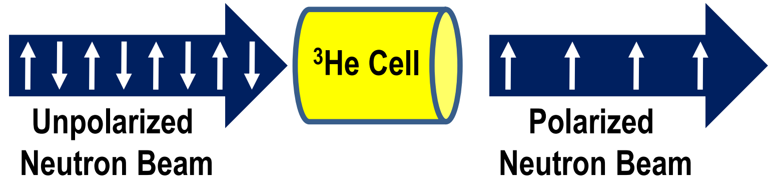


Multichannel Curved Guide
Fabricated by Swiss Neutronics

80m Guide for HRPD at J-PARC
Fabricated by Swiss Neutronics

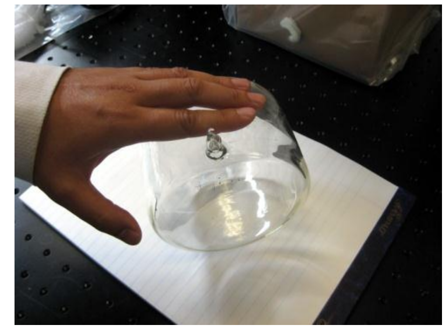
Guide Installation at ISIS

Polarizers and Spin Manipulators

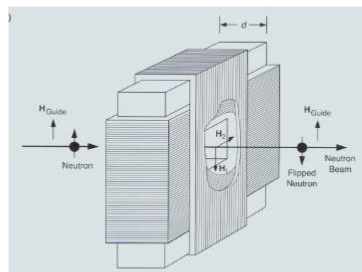


Heussler Monochromator
AlCuMn

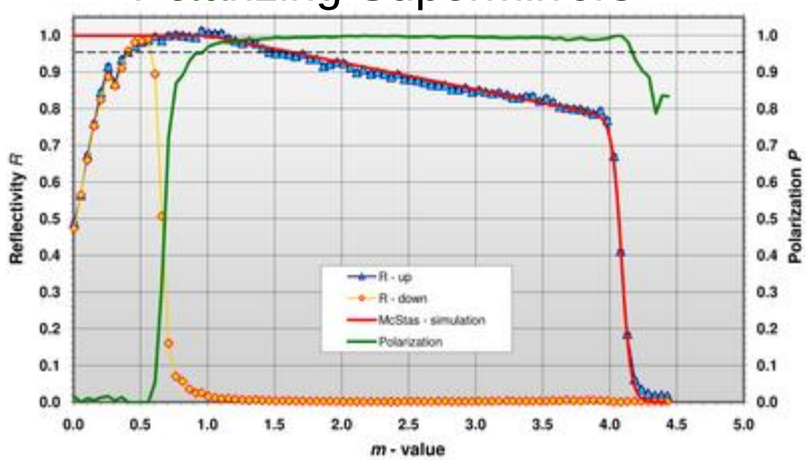
^{3}He Spin Filters



Larmor Precession Flipper



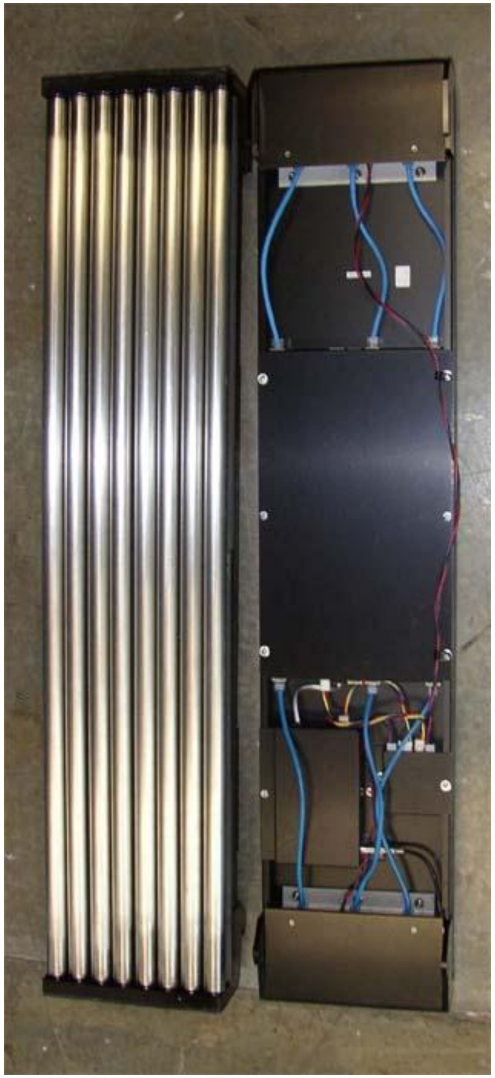
Polarizing Supermirrors



Spherical Neutron Polarimetry

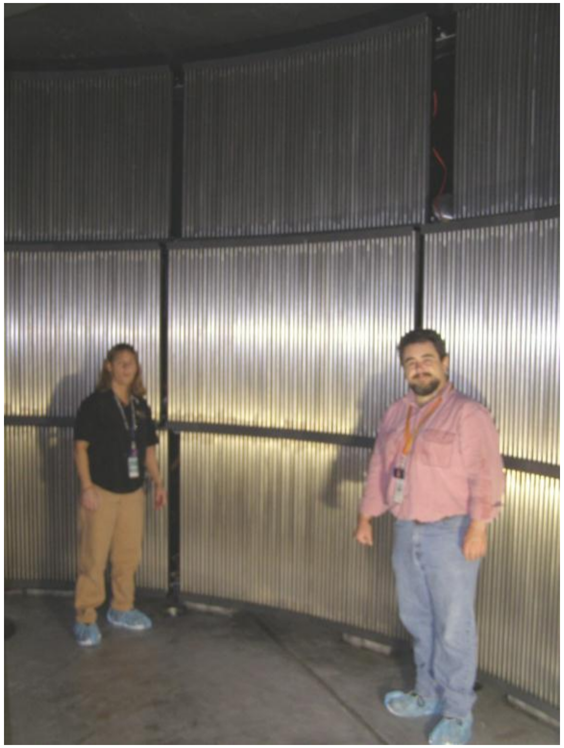
POLI-HEiDi at FRMII

Neutron Detectors: ^{3}He



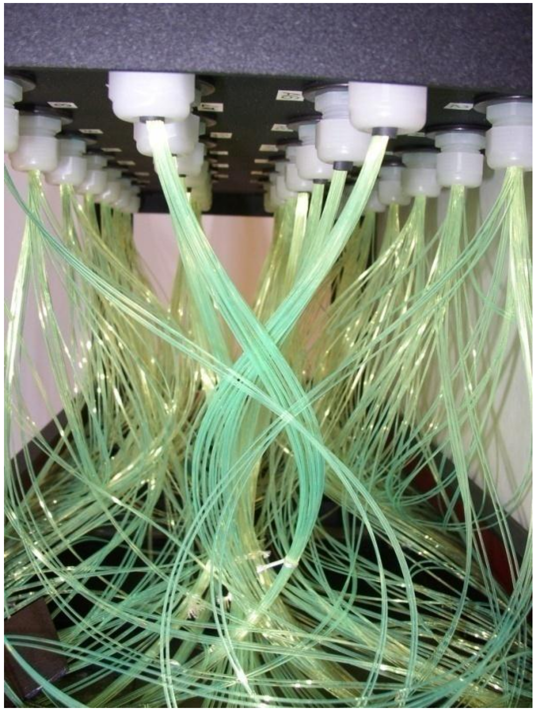
- **Approximately 75% of the detectors for neutron scattering use ^{3}He**
- **These detectors are efficient, stable, low noise, have excellent gamma discrimination, and good timing**
- **Unfortunately they are a thing of the past**

ARCS Detector Array
930 ^{3}HE LPSD's



Neutron Detectors: Scintillators

- Wavelength-shifting fiber detector developed for powder diffraction applications
- Blue scintillation light is shifted to green and captured in the fibers
- Uses a $^{6}LiF/ZnS:Ag$ scintillator pressed to increase density
- 308 × 152 pixels – 5mm wide and 50mm tall



Neutron Detectors: Anger Cameras

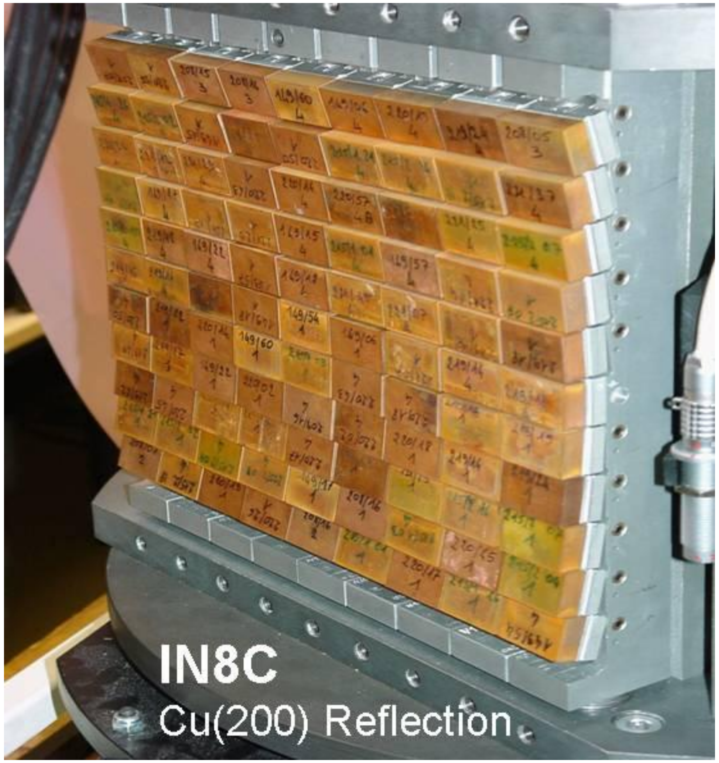
- The Anger camera optics package maps the scintillator (2mm GS20 Li glass) area to the 6mm x 6mm PMT anodes
- Fit measured light cone with a 2-gaussian function to determine neutron position (current resolution is 0.8mm)
- Developed for single crystal instruments

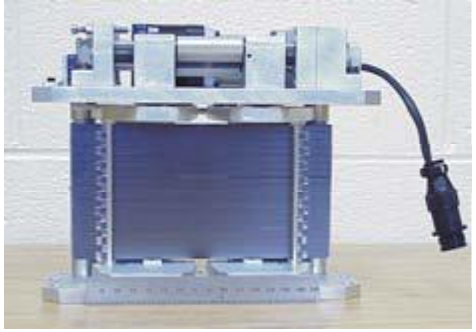
Detector Performance Affects Instrument Design

- Detector resolution and count rate often drive instrument development.
- Rule of Thumb: the optical resolution of a beamline should not exceed the spatial resolution of the detector.
- It is now possible for the neutrons scattered by the sample to saturate the detector so that the detector limits the performance of the instrument.
- ^{3}He for detectors will be in short supply for the foreseeable future. Future instruments will have to adapt to the new detector technologies.

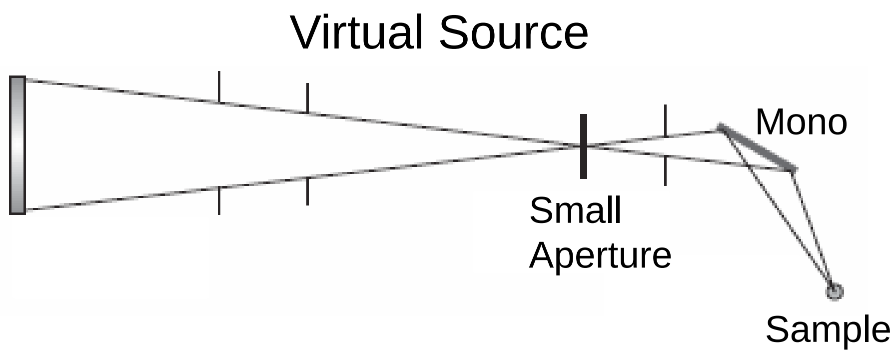
Neutron Optics: Focusing

Doubly focusing Cu monochromator at the ILL

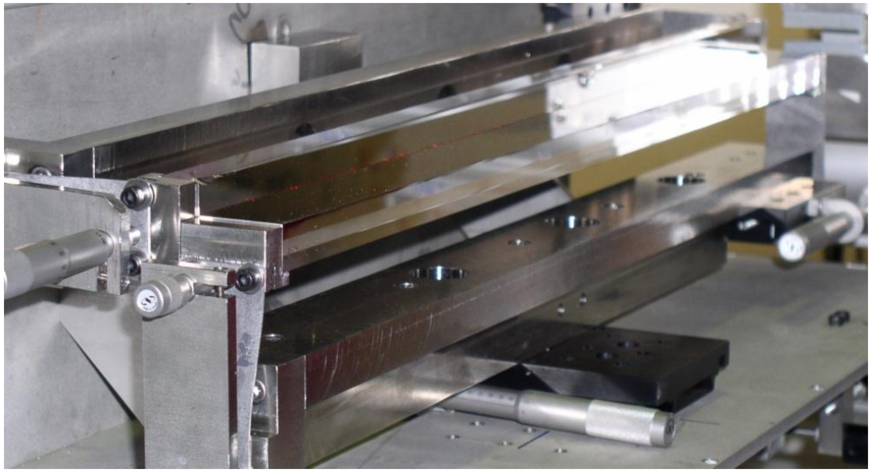


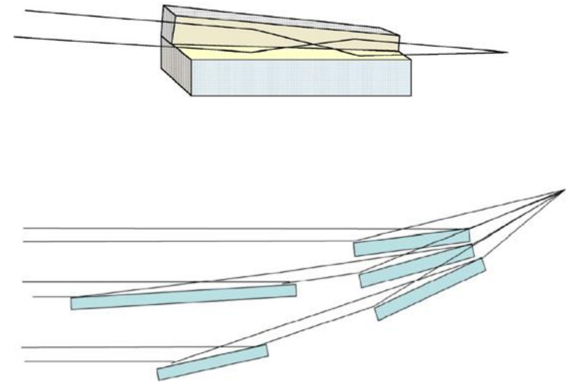


Double focusing "Popovici" monochromator. The vertical curvature is fixed while the horizontal curvature is variable by bending stacks of thin silicon wafers. The gain is achieved both by spatial focusing and 'wavelength focusing'.

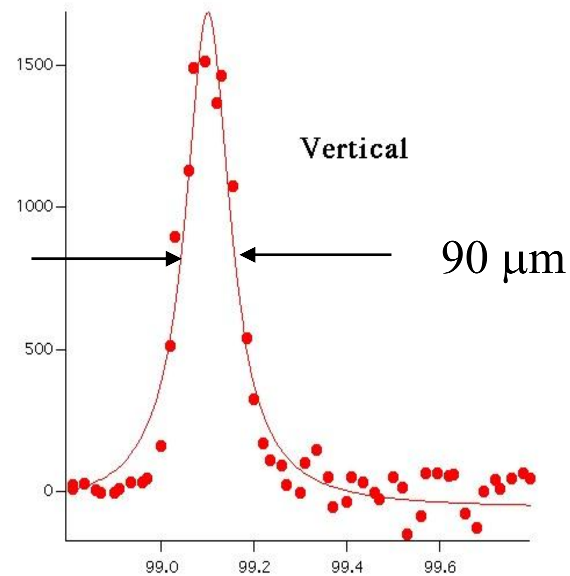


Neutron Optics: Focusing



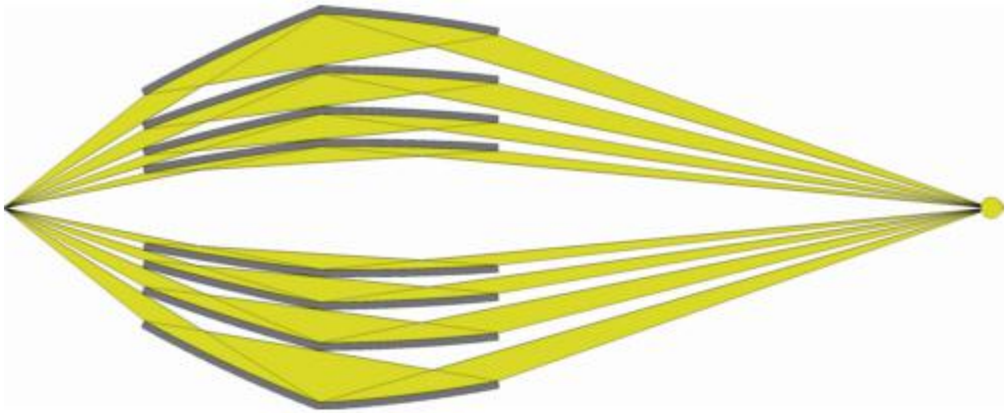


- **Focusing Mirrors :**
  - Develop a nested advanced KB mirror system to make a more compact assembly and to achieve the highest performance (Gene Ice, ORNL).
  - Identify applications where focusing optics can replace neutron guides and offer better performance.



Neutron Optics: Focusing

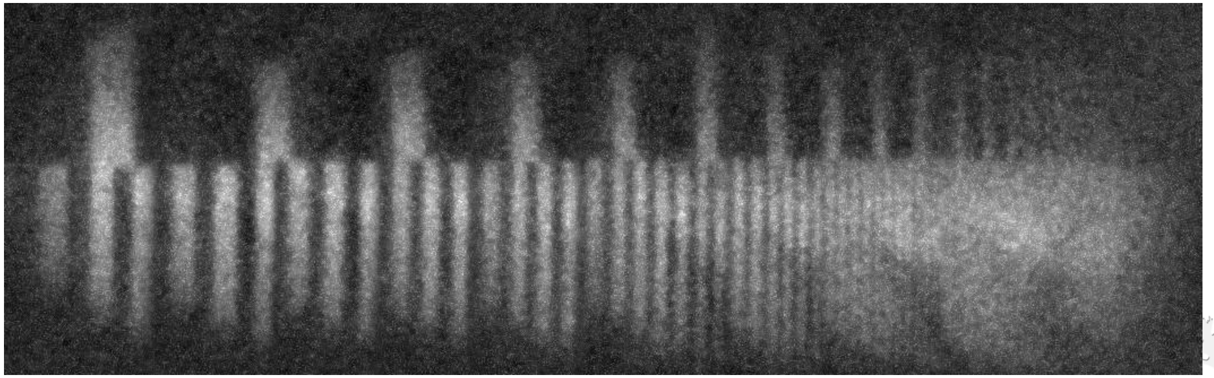
- **Wolter Optics for focusing beams with large cross-sections (Boris Khaykovich at MIT and Michael Gubarev at NASA)**



Optical path for Wolter optics

An X-ray optic module with 12 nested mirrors

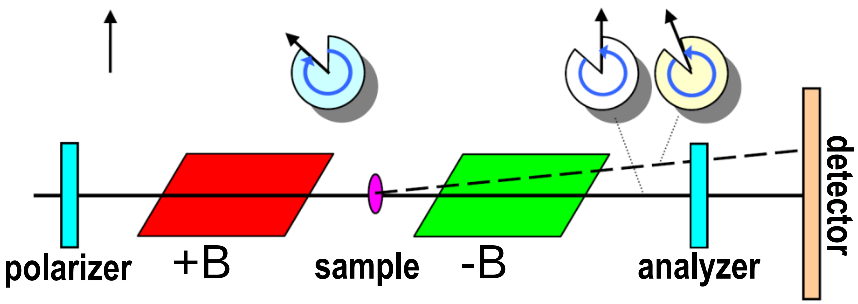
Image of a calibration grating using the X-ray optic in a neutron beam

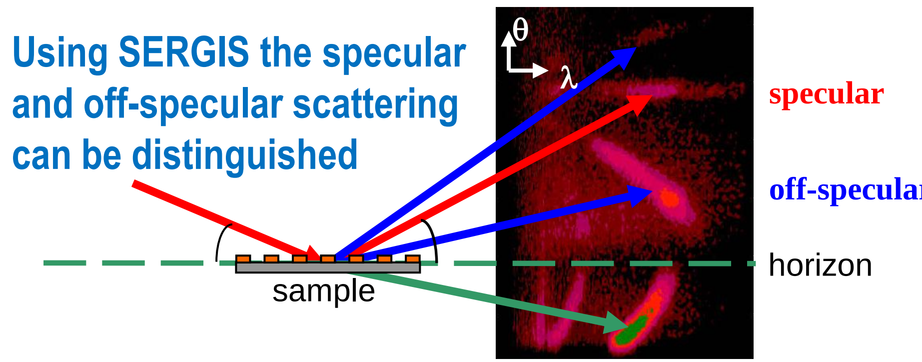


New Instruments: SERGIS

Spin-Echo Scattering Angle Measurement:

The neutron spin precesses through two parallelogram-shaped magnetic fields in opposite directions. For scattered neutrons the path-length through the two parallelograms is different resulting in a net change in the spin angle.

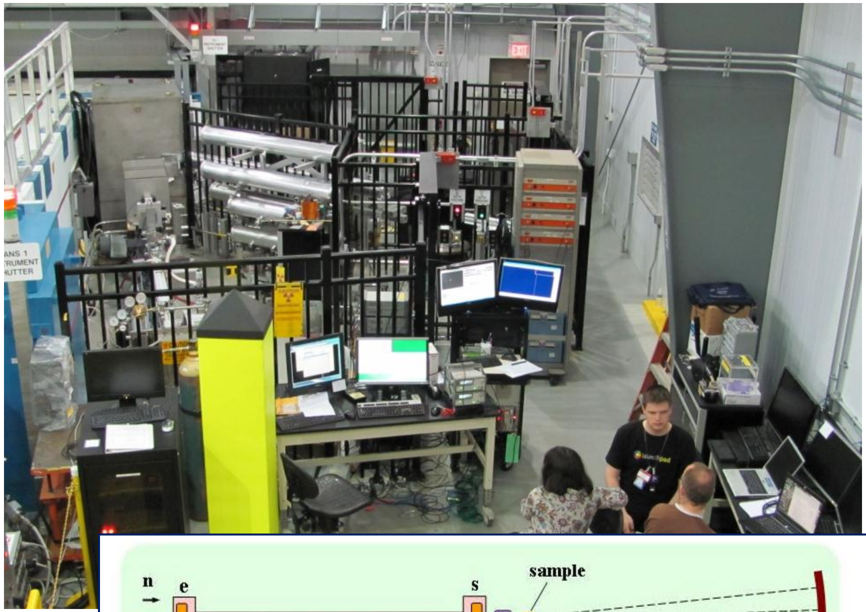


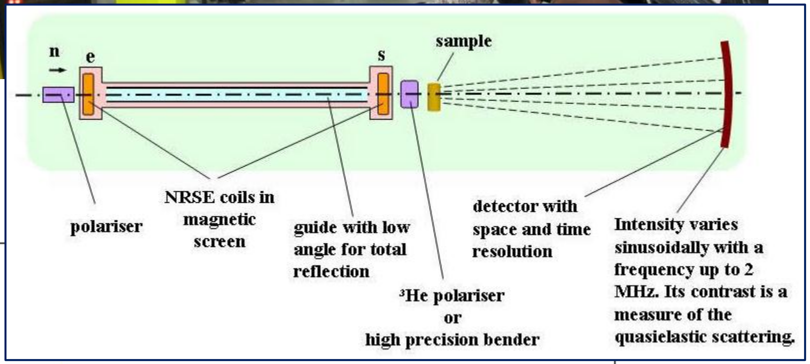


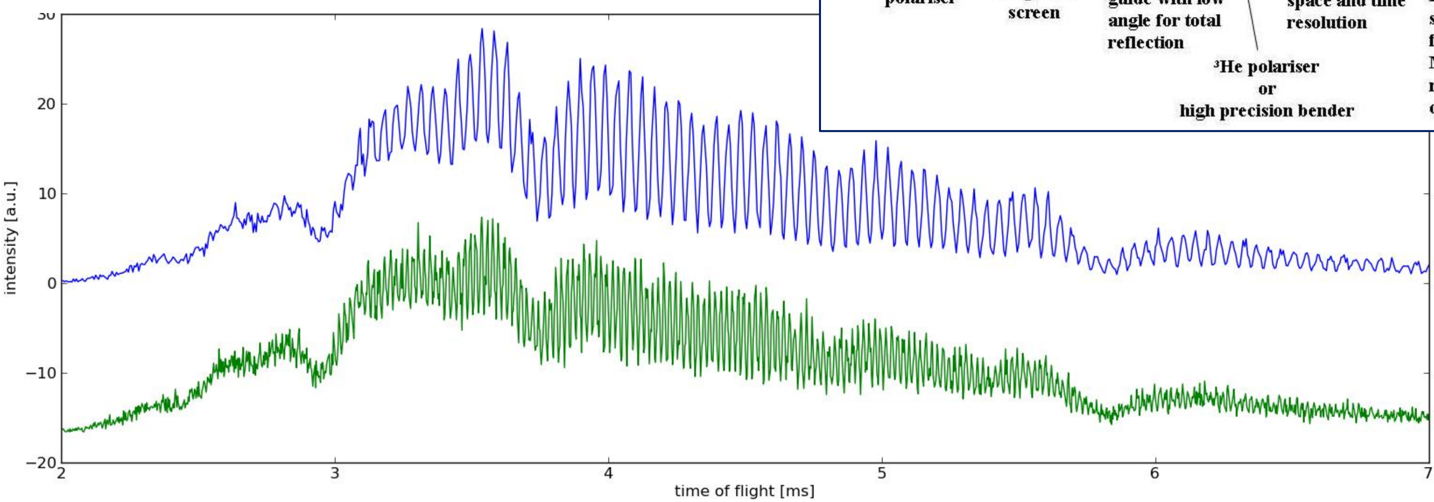
- Real space correlation lengths up to 20 microns (and beyond?)
- Does not require tight collimation for high resolution
- Can be used to probe the in-plane correlations of thin films and interfaces.

New Instruments: MISANS

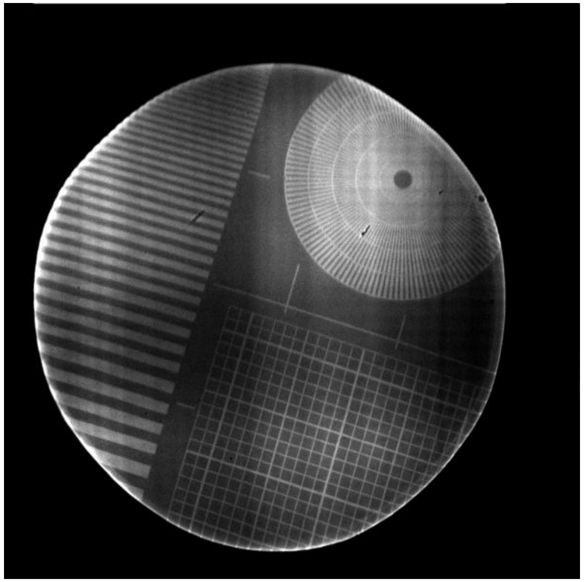
- Setup TOF MISANS instrument prototype using the "MIEZE box" from the MIRA beamline at FRMII
- Robert Georgii, Georg Brandl, Jyotsana Lal, Markus Bleuel
- Used MISANS prototype to study dynamics (paramagnetic chiral fluctuations) above T_c in MnSi.

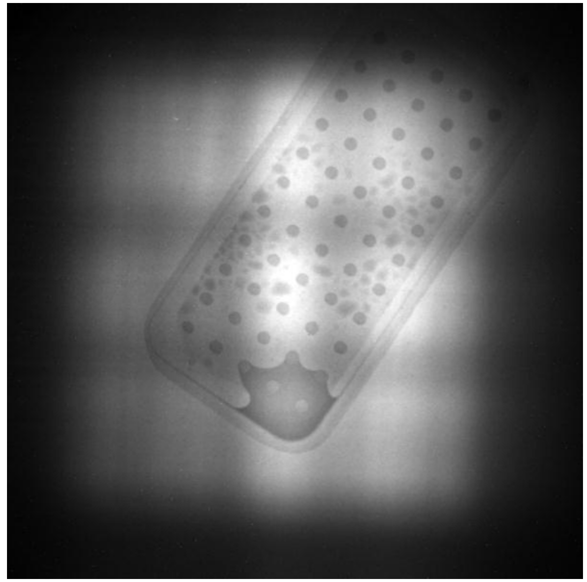


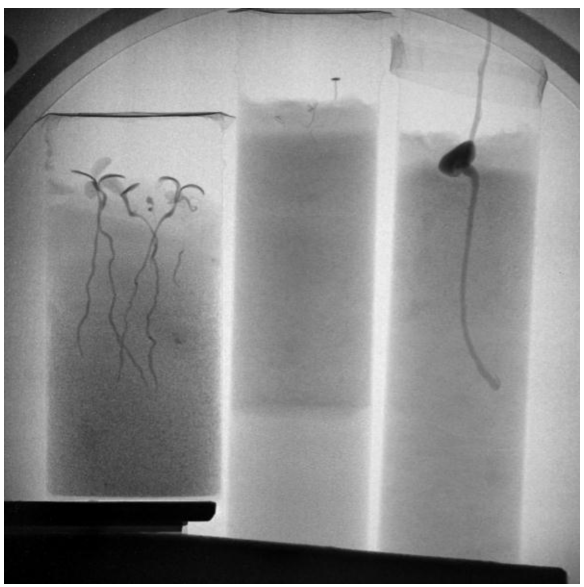


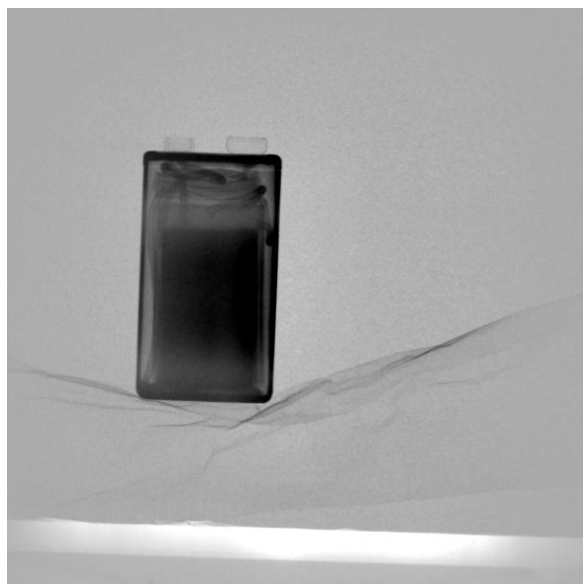


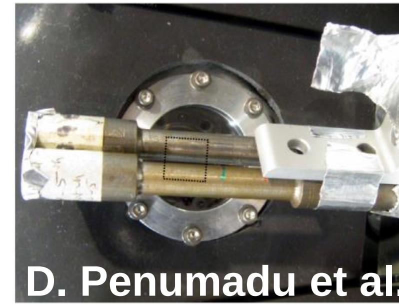
New Instruments: Neutron Imaging

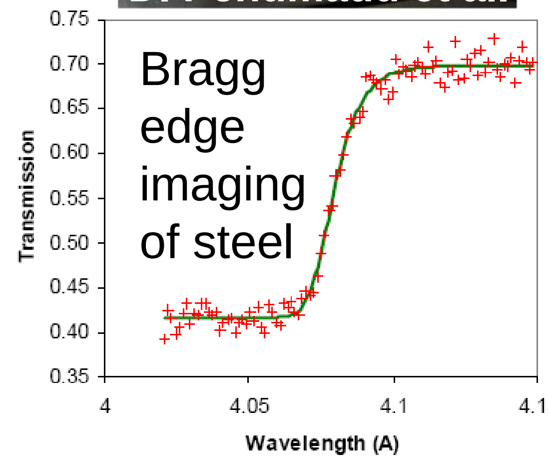




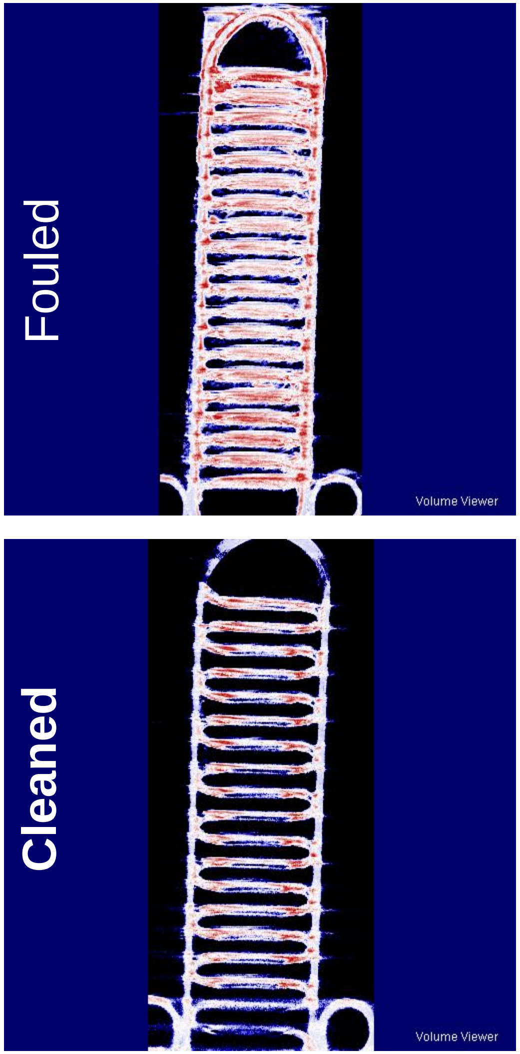






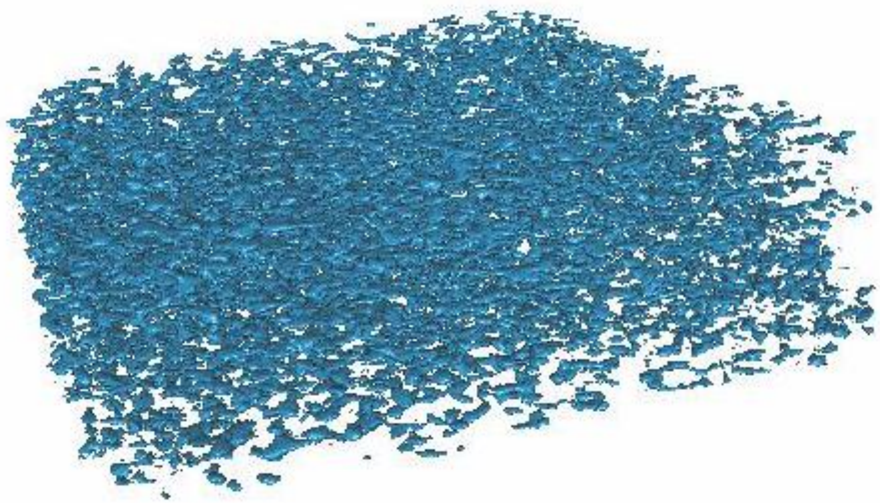


New Instruments: Neutron Tomography



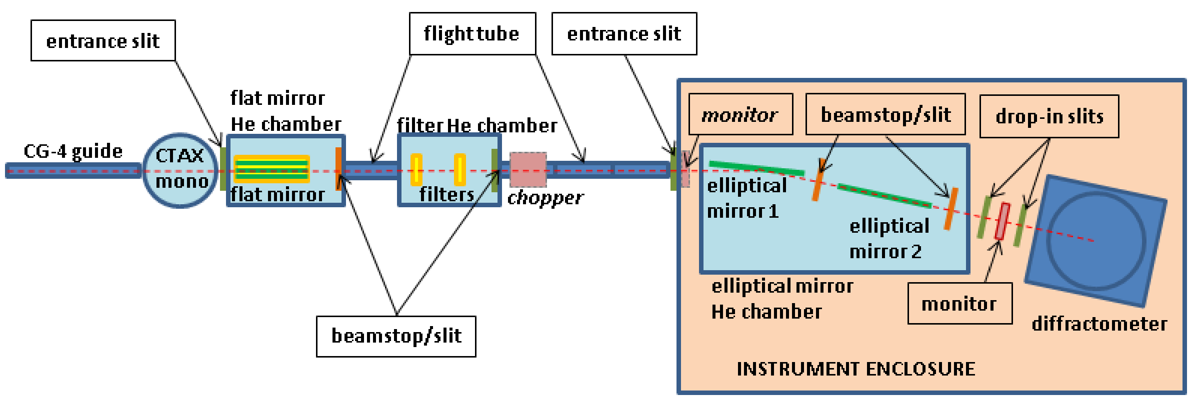
Diesel EGR Cooler Tube Sections
M. Lance, H. Bilheux, K. Willis, A. Strzelec

Carbon foam matrix in a Li battery
(H. Bilheux and S. Voisin)



New Instruments: IMAGINE Diffractometer

- **The IMAGINE beamline represents a new concept in neutron optics where the beam is transported by reflection off a discrete set of individual neutron mirrors rather than by a conventional neutron guide.**
- **The instrument requirements call for both the implementation of a wavelength band pass filter ($\lambda_{min} < \lambda < \lambda_{max}$) as well as focusing of the beam onto the sample position.**
- **The use of individual mirrors in the design allows for more freedom to incorporate these features into the beamline optics.**



Concluding Remarks

- **Instrument design is driven by the needs of the scientific community coupled with the source capabilities along with advances in neutron optics and detectors.**

- **In the near term instrument development will be primarily focused on:**
  - **Focusing optics**
  - **Polarization**
  - **Detectors**
  - **Instrument development infrastructure (computer simulations)**
  - **New techniques and applications**
  - **Source / moderator development**